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Washability of Trace Elements in Product (Marketed) Coals from Illinois Mines

Ilham Demir, Rodney R. Ruch, John D. Steele, and Saleem Khan

Ken K. Ho
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Illinois Clean Coal Institute
Carterville, IL 62918

Final Report (revised) to the Coal Research Board
Illinois Department of Energy and Natural Resources
through the Illinois Clean Coal Institute

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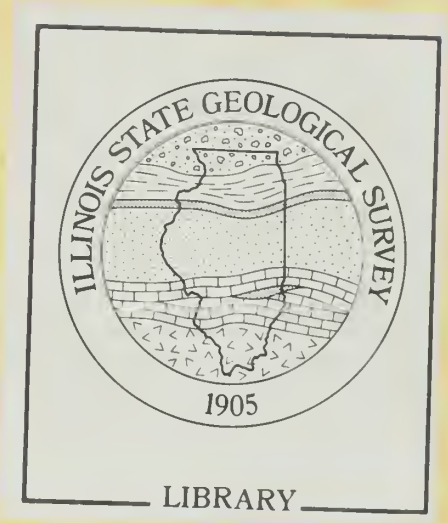
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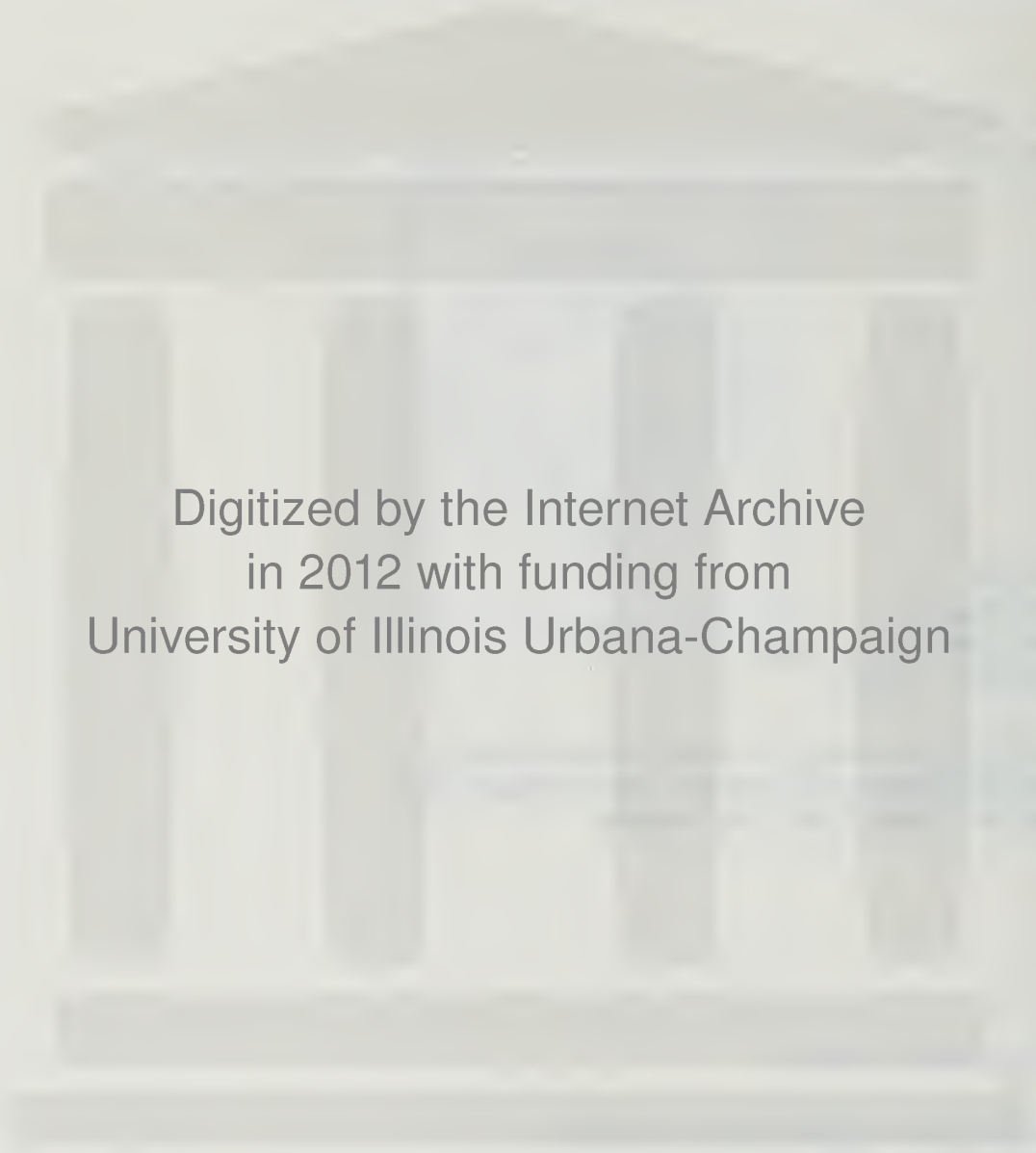

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ABSTRACT

In the past, washability data on trace elements in Illinois coals were generated mostly using float-sink methods, which cannot be used to estimate the performance of froth flotation or column flotation circuits. There is a particular lack of washability data on product (as-shipped) coals from modern preparation plants. The goal of this study was to provide the needed froth flotation washability data on trace elements in as-shipped Illinois coals.

Thirty-four coals, as shipped by Illinois mines, were ground to -100, -200, and -400 mesh sizes. Each ground sample was cleaned using a froth flotation/release analysis (FF/RA) test procedure. Concentrate and tailing fractions from the FF/RA tests were analyzed for ash and moisture; some samples were also tested for sulfur (S), heating value (Btu), and trace and minor elements. A composite sample having 80% of the total combustibles of the feed coal was prepared for each FF/RA test by combining the concentrates from that test in proportion to their ash contents. The composite samples were analyzed for trace and minor elements. The analytical data were used to evaluate the removal of ash, S, and trace elements from the as-shipped coals. The data indicate that, at 80%-combustibles recovery, as much as 69%, 76%, and 83% reductions in ash content can be achieved for the -100, -200, and -400 mesh sizes, respectively. The average reductions for trace elements were generally less than those for ash. However, reductions for some elements in individual samples approached or exceeded reductions for ash.

One of the as-shipped coals was subjected to FF/RA tests at -100 and -400 mesh sizes to investigate mass balances for ash, S, and for some trace and minor elements. Analytical results on concentrates and tailings from these FF/RA tests indicate mass balances within experimental errors.

OBJECTIVE

The objective of this study was to evaluate the beneficiation potential for trace elements in 34 coals, as shipped by Illinois mines, by applying a surface-based, fine-coal cleaning process. The term washability, which conventionally refers to float-sink data, is used in this report to describe data on the reduction of ash yield, S, and trace and minor elements in coal through the use of a special froth flotation procedure known as "release analysis." The data will be helpful in evaluating environmental requirements for noxious emissions at power-generating plants. The availability of trace element washability data will also permit matching specific coals with prospective markets (e.g., in advanced gasification processes and in the production of synthetic organic chemicals). To meet our objective, we conducted the following specific tasks.

1. Quality assurance/quality control (QA/QC): an existing Illinois State Geological Survey (ISGS) QA/QC plan was modified and applied during all phases of this study.
2. Sample preparation: samples collected during 1992-1993 and stored under nitrogen gas were used. Representative splits of the samples were ground to three different sizes (-100 mesh,-200 mesh, and -400 mesh) for the washability tests.
3. Washability (release analysis) tests: trace element cleanability of coal at fine to ultrafine particle sizes was evaluated using a special froth flotation process called release analysis.
4. Chemical analysis: the products from the release analysis tests were analyzed for moisture, ash, S, heating value, and trace and minor elements.

INTRODUCTION

The availability of trace element washability data could help encourage the use of Illinois coal products given the advent of new and improved technologies and expanding opportunities for exporting to foreign markets, as well as the requirements of recent environmental legislation.

The efficiency of cleanability from traditional density or float-sink separation of fine coal in the laboratory may not be achievable with large-scale cleaning processes used in industry. It is important, therefore, to develop a washability database that has industrial application. The washability testing process we used has the potential for economical and commercial applications. The process uses multi-stage flotation in a standard sub-aeration flotation cell to

generate special washability (release analysis) data. The release analysis data have been demonstrated to correlate well with optimum performance of standard fine-coal cleaning procedures, namely froth flotation and column flotation (Forrest 1990, Honaker and Paul 1994).

BACKGROUND

Trace and Minor Elements in Coal and Coal Combustion

A study by the U.S. National Committee for Geochemistry (National Research Council [NRC] 1980) discussed the potential health hazards of various trace elements that might be encountered during the development and utilization of coal. Three categories of elements of environmental concern were identified with respect to coal.

- Of greatest concern: As, B, Cd, Pb, Hg, Mo, and Se.
- Of moderate concern: V, Cr, Ni, Cu, Zn, and F.
- Of minor concern: Li, Na, Sr, Ba, Mn, Co, Ge, Cl, Br, and radioactive elements Ra, Po, Rn, Th, and U.

These judgments were made on the basis of known toxicity, levels of occurrence of each element in coal, and anticipated mobility upon coal combustion or disposal of coal ash. These Eventual emission standards should be based on valid biological data.

The Clean Air Act (CAA) Amendments of 1990 (Public Law 101-549, 1990) includes 16 elements that occur in coal in a list of 189 "Hazardous Air Pollutants" (HAPs): As, Be, Cd, Cl, Cr, Co, F, Hg, Mn, Ni, P, Pb, Sb, Se, Th, and U. Radioactive isotopes derived from U and Th, such as Po, Ra, and Rn, are also implicated as HAPs. A parallel regulation to classify certain elements in coal as HAPs has also been considered in Illinois (Illinois Pollution Control Board 1990).

The HAP elements are present in all coals, not only those from Illinois, but their concentrations can vary considerably between coals (Gluskoter et al. 1977, Swanson et al. 1976, Zubovic et al. 1979, 1980, Cahill et al. 1982, Harvey et al. 1983). Electrical utilities are not currently required to meet any standards for HAPs emissions. This may change, however, after the U.S. Environmental Protection Agency (U.S. EPA) completes its risk assessment studies and establishes emission standards. Coal-burning utilities may eventually be required to monitor the amount of each HAP element emitted to the atmosphere from their power plants.

Klein et al. (1975) conducted mass balance studies on the Allen cyclone boiler power plant at Memphis, Tennessee, using coals from Illinois and western Kentucky. These studies indicate that most coal-derived Hg, some Se, and probably most Cl and Br are released as gases to the atmosphere. The elements As, Cd, Cu, Ga, Mo, Pb, Sb, Se, and Zn were concentrated in the fly ash and partially released to the atmosphere attached to small fly ash particles. The electrostatic precipitator removed about 96.5% to 99.5% of the fly ash. Kaakinen et al. (1975) measured the concentrations of 17 elements in a mass balance study of a power plant fueled with a western coal. The elements Pb, Cu, Zn, As, Mo, Hg, and Se were found to be partially volatilized. Natusch et al. (1974) observed that certain elements, especially As, Sb, Cd, Pb, Se, and Tl, were more concentrated on smaller, respirable-sized fly ash particles.

Swaine (1989) reviewed the environmental aspects of trace elements in coal. Modern electrostatic precipitators can trap as much as 99% of the fly ash. Trace elements emitted into the atmosphere during combustion are thus either attached to ultrafine fly ash particles or in a gaseous state. Swaine concluded that, in general, no trace element posed a significant environmental problem. This conclusion was made assuming the use of state-of-the-art electrostatic precipitators and the use of coals with no exceptionally high concentrations of those noxious elements that would be emitted in a gas phase or attached to small fly ash particles that can pass through electrostatic precipitators.

Removal of Trace Elements from Coal

Reviews summarizing progress in the removal of trace elements via coal cleaning include Jacobsen et al. (1992), Norton et al. (1985, 1986, 1992), Kaiser Engineers (1989), Norton and Markuszewski (1989), Streeter (1986), Wheelock and Markuszewski (1981, 1984), National Research Council (1979, 1980), and Mezey (1977).

Several studies have evaluated the removal of trace elements from coal through various cleaning methods. Deep physical cleaning of coal was reported to significantly reduce the level of most trace elements (Gluskoter et al. 1977, Cavallaro et al. 1978, Harvey et al. 1983) as shown by float-sink testing. There is, however, a lack of data on the trace element washability of product coals from modern preparation plants. In general, physical cleaning becomes efficient (70%-90% removal) if a high degree of comminution is used to free mineral matter from the coal macerals. Those trace elements associated with the macerals, however, are not removed. Their concentrations are actually increased in the cleaned coal. Studies tracking trace element removal using chemical means indicate better removal; however, costs would be quite high.

Float-sink separation studies have shown that significant reduction can be achieved for some trace elements through conventional coal cleaning; however, the coarse particles (approx. > 3/8 in.) generally limit the amount of minerals liberated. Extensive ISGS float-sink studies (Gluskoter et al. 1977, Fiene et al. 1979, Harvey et al. 1983) on Illinois coals indicate that many elements (As, Ba, Ca, Cd, Fe, Mn, Mo, Pb, Tl, and Zn) have strong inorganic association and can be removed to a significant degree (50% or greater). Other elements (B, Be, Ge, Ni, Sb, U, and V) are strongly associated with organic matter and are generally not removed by physical cleaning. Some 32 other elements showed indications of mixed association. However, even the organically associated elements may actually occur in disseminated minerals that are not removed by float-sink separation at coarse particle sizes. Kuhn et al. (1980) found differences in trace element/mineral association and possible cleaning potential for an eastern seam (Pittsburgh 8) and a western seam (Rosebud). For example, in the Rosebud coal, Sb was classified to be associated with the organic fraction; in the Pittsburg Coal, it largely shows inorganic association. Cavallaro et al. (1978) reported on the float-sink behavior of eight elements (Cd, Cs, Cu, F, Hg, Mn, Ni, and Pb) in ten coals from various producing areas of the United States. Although the concentration of individual trace elements in the feed coal varied within and between regions, the removal of the heavier fraction (>1.6 S.G.) resulted in significant reductions in the 14-mesh clean coal product for all tested coals. Depending upon the geographical region, 64% to 88% of the composite trace element concentrations were in the 1.6-S.G. sink fraction.

Akers and Dospoy (1992) reported washability data on the Upper Freeport coal for As and Ni at several size fractions; they observed better removal at the smaller sizes. They also presented data on reductions for ten trace elements for four coal seams at several combustible recoveries using conventional gravity separations.

Ford et al. (1976) demonstrated that cleaning at a top size of 30 mesh via a concentrating table was effective in partially removing Hg, Pb, As, Mn, and Se from eight diverse coal types. Removal ranges were reported for Hg (3%–68%), Pb (8%–63%), As (11%–67%), Mn (9%–6%), and Se (2%–61%). Ford and Price (1980) reported results of conventional and non-conventional cleaning of 20 run-of-mine coals. The elements As, Cd, Cr, Co, Cu, F, Pb, Mn, V, and Zn, as well as most major ash elements, were significantly removed. Ford and Price (1982) reported on trace element removal via heavy media cyclone cleaning. Average percentages of the original amount of trace elements that remained in the clean fractions for four Appalachian and two midwestern coals were as follows: As, 53%; B, 98%; Be, 75%; Cd, 54%; Co, 63%; Cr, 60%; Cu, 60%; F, 49%; Hg, 89%; Mn, 37%; Ni, 62%; Pb, 32%; Sb, 91%; Se, 67%; V, 76%; and Zn, 51%. Conzemius et al. (1988) determined the effect of cleaning with a heavy media cyclone on 75 elements. Although most elements followed the ash, cleaned coal was enriched in Be, Mo, U, I, Co, and Sb.

Kulinenko and Barma (1990) used a combination of screening, density separation, jigging, flotation, centrifugation, and vacuum filtration, and they monitored 29 trace elements in the various streams. Arsenic and Hg were most abundant in jigging refuse. In density separation refuse, F and Ga were most abundant; Hg, Be, and Ge were least abundant. Cesium was least abundant in flotation refuse.

Capes et al. (1974) reported that levels of As, Cs, Pb, Mn, Mo, Ni, and V were reduced by 50% to 80% during separation by oil agglomeration. Knott et al. (1985) reported on trace element reduction comparisons obtained by oil agglomeration, froth flotation, and float-sink processes on Australian coals. The OTISCA process, an oil agglomeration approach using a fluorocarbon liquid (freon), indicated more than 90% removal of As, Cd, and Pb from coal (Jacobsen et al. 1992).

A combination process of froth flotation and oil agglomeration known as aggregate flotation was able to remove greater than 50% of Cd, Co, Cr, Li, Mn, Na, Sb, Sr, Th, and V from Illinois coals (Buckentin et al. 1985). A combination of heavy media cyclone or table separation and advanced froth flotation approach utilizing microbubble processing (Bechtel National Inc. 1988) removed 80% to 90% of As, Be, Co, F, Ni, Pb, Sb, Th, U, Cr, and Sc from Illinois coal.

The LICADO process (Jacobsen et al. 1992), based on surface-separation using liquid CO_2, indicated only moderate separation for As, Ni, and Pb.

Limited data for Battelle hydrothermal and TRW/Molten caustic leachings (Jacobsen et al. 1992) show high removal of Pb but only mixed reduction for Cd, Ni, Se, and As. Data on the Battelle Alkaline desulfurization process for three Ohio coals indicate high (>70%) removal for Li, Ba, Be, B, K, P, Mo, V, As, and Ba (Mezey 1977, Stambaugh et al. 1979).

In the Jet Propulsion Laboratory chlorinolysis process, chlorine gas is passed through a slurry of finely ground coal, organic solvent, and water at 50° to 100° C (Jacobsen et al. 1992, DuFresne and Kalvinskas 1980). Removals were high for Pb, medium for As, and low for Cd, Hg, and Se.

The Meyers process (Mezey 1977, Hamersma et al. 1974) uses and regenerates $Fe_2(SO_4)_3$ and is said to remove pyrite effectively. In a study of some western, eastern interior, and Appalachian coals, As, Zn, Cd, Pb, Ni, Mn, Cr, and other elements normally known to be associated with pyrite and other minerals were significantly reduced. The results for B, Be, Cu, F, Hg, Li, and V were somewhat mixed.

Norton et al. (1986) reported on the comparative treatment of the Herrin (Illinois No. 6) coal using molten NaOH/KOH or 1.0 M Na_2CO_3 addition under elevated temperature/pressure conditions followed by acid wash. Levels of Mn, Pb, Rb, Sr, and Zn were lowered by 75% or more, while those of Ba, Cd, Cr, Ni, and Se were lowered by 30% to 60%. They also reported results, obtained by the TRW Gravimelt process, where levels of As, Be, Cd, Hg, Pb, Se, and Sr were reduced by 75% or more. Kuhn et al. (1980) reported on some 52 trace and minor elements in eastern and western coals that were subjected to float-sink separation and extensive extractions with dilute HNO_3 and HF, followed by washing with water. This approach indicates the amount of trace elements that would remain in the coal after an exhaustive physical and chemical cleaning.

In a previous study, Demir et al. (1994) generated data on trace elements in 34 product (as-shipped) coals from operating Illinois mines and compiled existing ISGS data on channel and other samples. These coal data permit prediction of maximum possible emission levels for individual trace elements that would result from burning Illinois coals. The present study characterizes froth-flotation washability of trace elements in the same 34 product coals. The terms product coal, as-shipped coal, marketed coal, and washed coal are used interchangeably for the 34 samples investigated in this study. Because of the proprietary nature of the data, individual mine results are reported only by sample numbers and by multi-county regions.

EXPERIMENTAL PROCEDURES

Quality Assurance/Quality Control (QA/QC)

The ISGS's Quality Assurance/Quality Control plan was implemented for this study. The QA/QC plan includes the standard operating procedures for each analytical task and for sample preparation. Blank, blind, and replicate samples were analyzed to ensure data reliability. Detailed sample description, requests for analysis forms, unique sample identification numbers, and sample handling procedures were used. Further details of the QA/QC plan are available upon request.

Samples and Sample Preparation

Thirty-four samples of as-shipped coals collected from one mine and 33 coal preparation plants that were in operation in Illinois during 1992-1993 were used in this study. Details of the collection, preparation, and storage of the as-shipped coal samples are described in Demir et al. (1994).

-100 mesh samples Representative samples of the 34 as-shipped coals were passed through a jaw crusher and then a roll crusher to reduce the particle size of the coal to <3/8 in. and -4 mesh, respectively. A split of each -4 mesh size coal was then dry-ground in a hammer mill in conjunction with a -60 mesh screen. The ground samples were analyzed for particle size distribution on a Microtrac particle size analyzer. The particle size data indicated that about 90% of the ground material was -100 mesh size.

-200 mesh samples About 700 g of each -4 mesh coal (see preparation of -100 mesh samples above) was mixed with 700 mL of tap water and ground in a rod mill for 30 minutes. The coal slurry was filtered, split in half, and saved for froth flotation/release analysis (FF/RA) tests. A split of the filter cake was tested for particle size distribution. In general, the samples tested in the range of 90% -200 to -270 mesh. Several samples tested in the range of 90% -325 mesh and 80% -500 mesh. In those cases, grinding was repeated for less than 30 minutes to achieve a particle size distribution of about 90% -200 mesh.

-400 mesh samples About 700 g of each -4 mesh coal was mixed with 700 mL of tap water and ground in a rod mill for about 60 minutes. The coal slurry was filtered, split in half, and saved for the FF/RA tests. Data on particle size analysis indicated a particle size distribution of 85% to 90% -400 mesh.

Froth Flotation Washability Procedure

The ground as-shipped samples were cleaned through froth flotation using the release analysis technique (Dell 1964, Forrest 1990). Figure 1 shows the systematic series of sequential flotations performed to obtain five concentrates and four tailings (the tailings are eventually combined for analysis) having different ash yield and concentrations of trace elements.

For the -100 mesh samples, a representative split (300 g, dry basis) was slurried with about 3.5 L of tap water in a conventional Denver froth flotation cell, conditioned with 0.4 mL of kerosene. Then 0.4 mL of frother (2-ethylhexanol) was added, and approximately 7 L of air per minute passed through the cell with the rotor set at 1,200 rpm. The resulting float (concentrate) fraction was again mixed with water and floated three times (adding 0.1 mL additional frother), and the corresponding tailings were collected. The resulting concentrate from the third flotation was again mixed with water, refloated, and then the float was collected at 20-second intervals (C1, C2, C3, C4, C5) and at varying air flow rates (2-8 L). This procedure generates the cleanest sample (C1) and progressively less clean samples (C2, C3, C4, C5) in addition to the lower grade tailings (T1, T2, T3, T4).

The same FF/RA procedure illustrated in figure 1, with a few changes in reagent concentrations, was applied to the -200 and -400 mesh samples. Filtered cakes were subjected to the FF/RA on the same day they were ground. Generally, 0.7 and 1.0 mL kerosene were used for the -200 and -400 mesh samples, respectively, in the first flotation. In some cases additional kerosene had to be added to condition the coal and prevent excess amounts of tailings. For both -200 and -400 mesh samples, 0.5 mL frother was added in the first flotation.

Chemical Analyses of Samples

All concentrates and tailings from the FF/RA tests were analyzed for moisture and ash, and some were tested for total S and heating value (Btu). A good empirical relationship was found between heating value and combustibles for all samples (fig. 2). Concentrates and tailings from two of the FF/RA tests were also analyzed for forms of S, Cl, and trace and minor elements. A composite

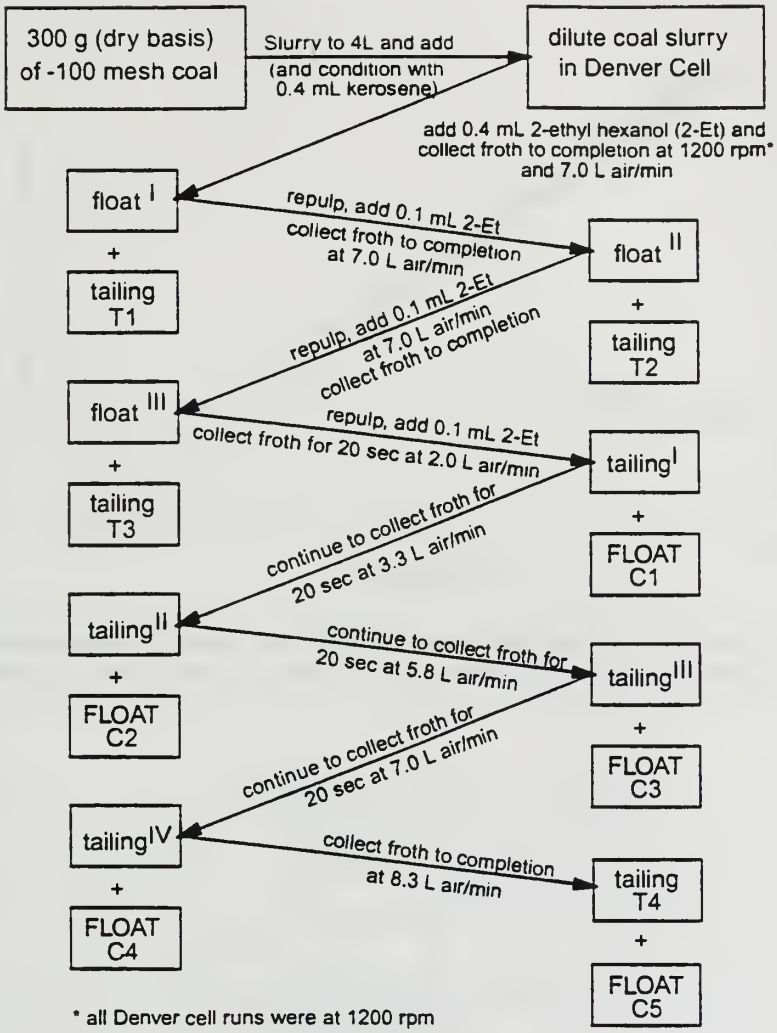

Figure 1 Froth flotation and release analysis approach.

sample containing 80% of the total combustibles of the feed coal was prepared for each of the FF/RA tests by combining the concentrates from that test in proportion to their ash contents. The composite samples were analyzed for ash, moisture, and trace and minor elements. All the analyses were carried out in accordance with strict ISGS QA/QC procedures. Methods of chemical analyses used and levels of their precision and accuracy are shown in table 1.

RESULTS AND DISCUSSION

Froth Flotation Washability

Release analysis curves for ash and sulfur Data are available to construct froth flotation washability (release) curves that show ash yield and S content of clean coal products at various values of combustibles recovery. As an example, two sets of curves from each of the four regions of the Illinois coal field (fig. 3; see Demir et al. [1994] for more information) are included in this report (figs. 4 and 5). Ash yield and S content of the FF/RA products vary depending on the type of coal, particle size used, and desired combustibles recovery. In general, production of low ash (2%–5%) and lower S (1.2%–2.4%) coals is possible in some cases. Data on ash yield and S for individual FF/RA fractions of all samples are available upon request.

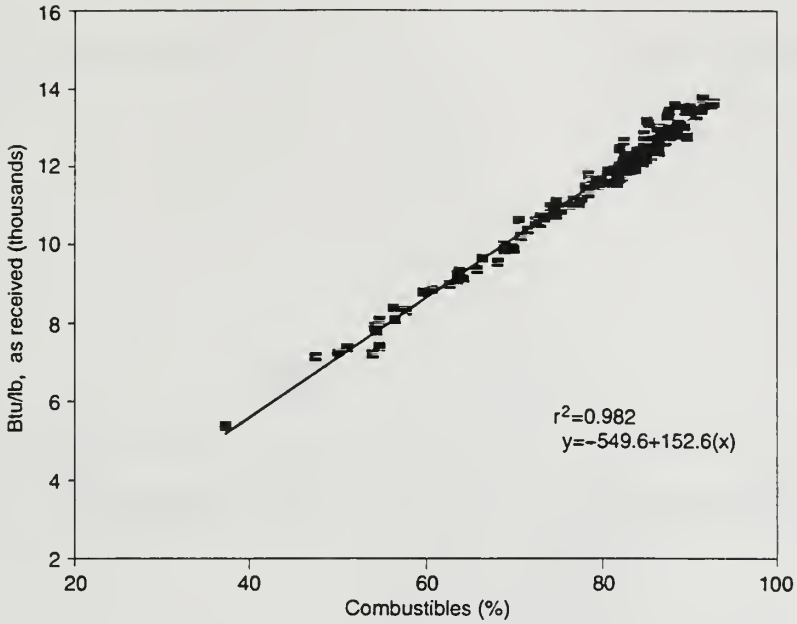

Figure 2 Relationship between heating value (Btu/lb) and combustibles (combustibles = 100 - % moisture - % ash) for 34 as-shipped Illinois coals and their FF/RA products obtained at −100 mesh size.

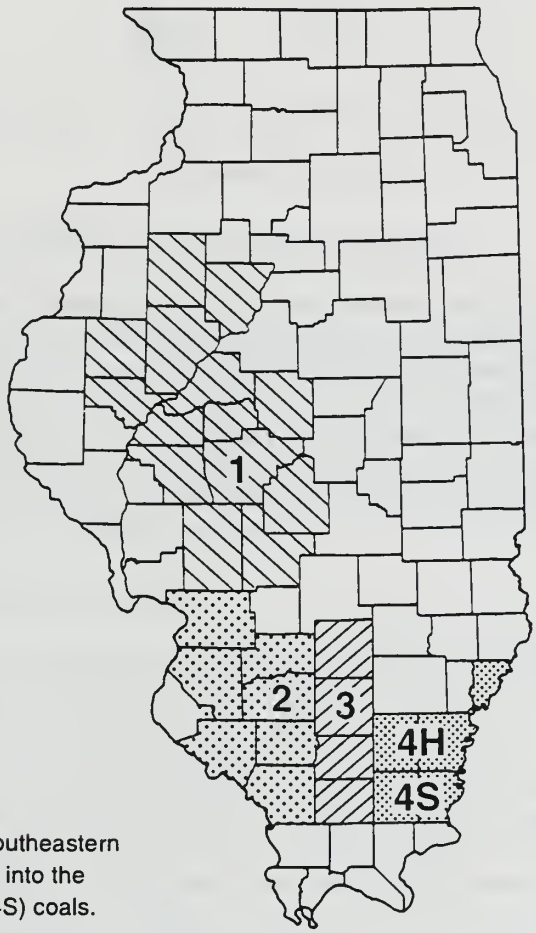

Figure 3 Sample regions. Southeastern Illinois is subdivided by seam into the Herrin (4H) and Springfield (4S) coals.

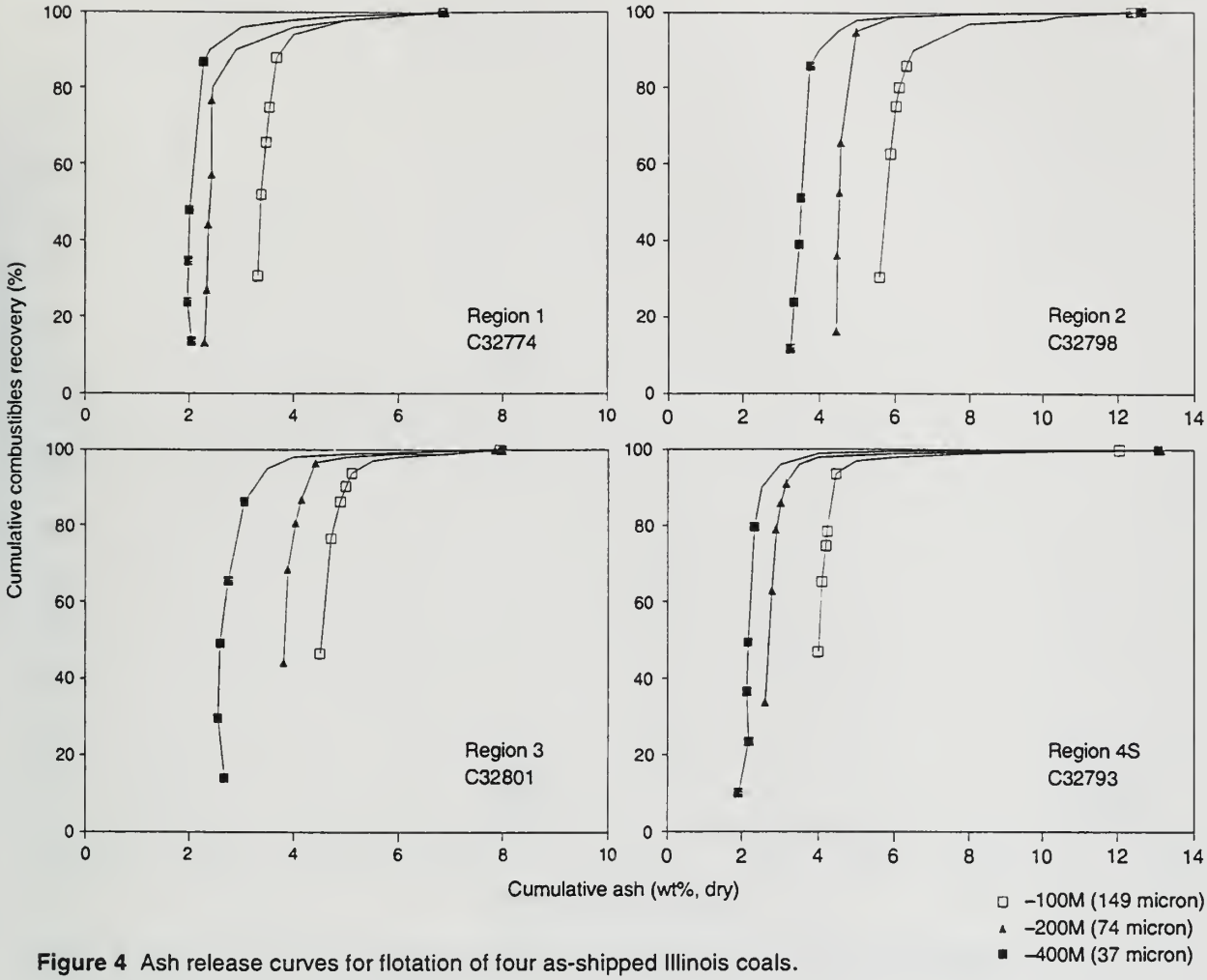

Figure 4 Ash release curves for flotation of four as-shipped Illinois coals.

Trace elements in 80%-combustibles recovery composites Data on ash yield, heating value (Btu/lb), and concentrations of HAP elements in as-shipped coals and in their 80%-combustibles recovery products from the FF/RA tests are given in table 2. All of the elements classified as HAPs in the CAA Amendments of 1990, except Cl, are included in table 2. Results on other trace elements, as well as minor elements, are available upon request. The heating values of the 80%-combustibles recovery composites were calculated using the empirical relationship given in figure 2, and the calculated values were then converted to a dry basis. Reductions in ash yield and HAP elements were calculated using the data from table 2:

$$\%\text{reduction} = ((C_{feed} - C_{clean})/C_{feed}) \times 100$$

where C_{feed} and C_{clean} are the ash yield or a trace element content in feed and clean coals, respectively. The reduction results for the -100 mesh FF/RA tests are given in table 3; those for the -200 and -400 mesh FF/RA tests are given in table 4.

The data in tables 3 and 4 indicate significant reductions for most of the samples considering that the FF/RA tests were performed on as-shipped coals, which themselves are already cleaned products from conventional coal preparation plants. Average reduction values generally increased as the particle size of the feed decreased from -100 mesh through -200 mesh to -400 mesh. The average reductions for most HAP elements were less than those for ash yield, as illustrated by four examples shown in figure 6. However, reductions for some elements in individual samples can approach or exceed reductions for ash yield.

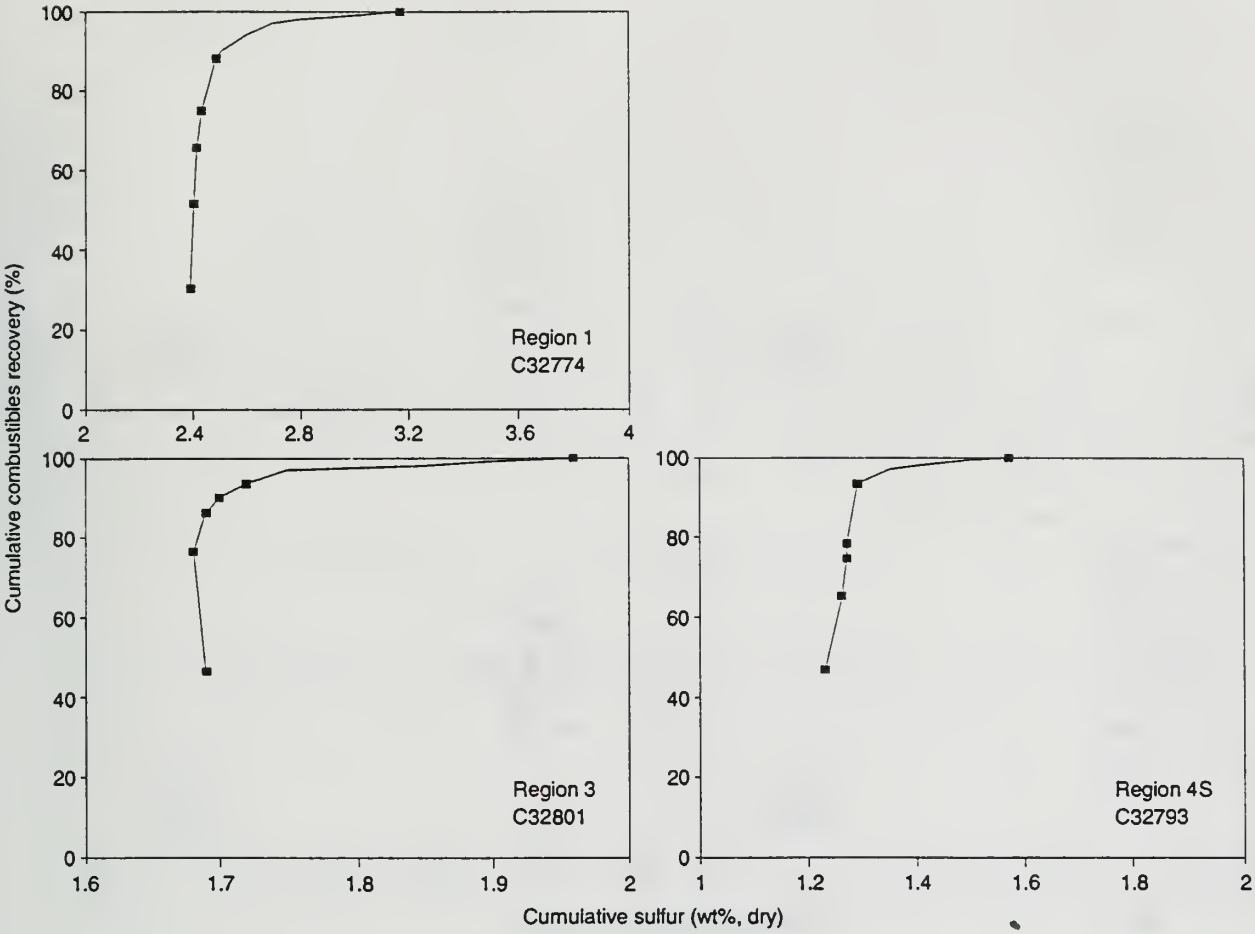

Figure 5 Sulfur release curves for flotation of three as-shipped Illinois coals (−100 mesh size).

Reductions for Mn and P approached or exceeded reductions for ash yield for the majority of the samples. A substantial portion of Mn is expected to occur in solid solution in calcite, and P is associated, perhaps primarily, with apatite in coal. Most of the calcite and some of the apatite occur as cleat fillings, nodules, and/or partings (Rao and Gluskoter 1973, Harvey et al. 1983); cleat, parting, and nodule minerals are more easily removed during coal cleaning than finely disseminated minerals. Those HAP elements that have lower reductions than ash yield are apparently enriched in finely disseminated mineral matter or in clay minerals that are generally trapped in the concentrates from the FF/RA tests.

Data on average concentrations of trace elements in as-shipped Illinois coals and in their FF/RA beneficiated products indicate that both as-shipped samples and the FF/RA products contain significantly less HAP elements than channel samples (fig. 7). In the −200 mesh FF/RA products, for example, average concentrations of As, Hg, and Se were reduced by 73%, 75%, and 46%, respectively, relative to their average concentrations in channel samples. These reductions are important because As, Hg, and Se are highly volatile during combustion and may become targets of air quality legislation.

Comparing results for a set of five as-shipped coals subjected to FF/RA at −100, −200, and −400 mesh indicates that, in general, additional beneficiation achieved by grinding the coal finer than −200 mesh is relatively small for the majority of HAP elements (fig. 8). This is likely a result of trapping of fine ash material in the concentrates for the majority of samples. Beneficiated coals, however, have higher heating value than feed coals. The reductions shown in figures 7 and 8 would, therefore, be greater if the concentrations were compared on a mg/MMBtu basis.

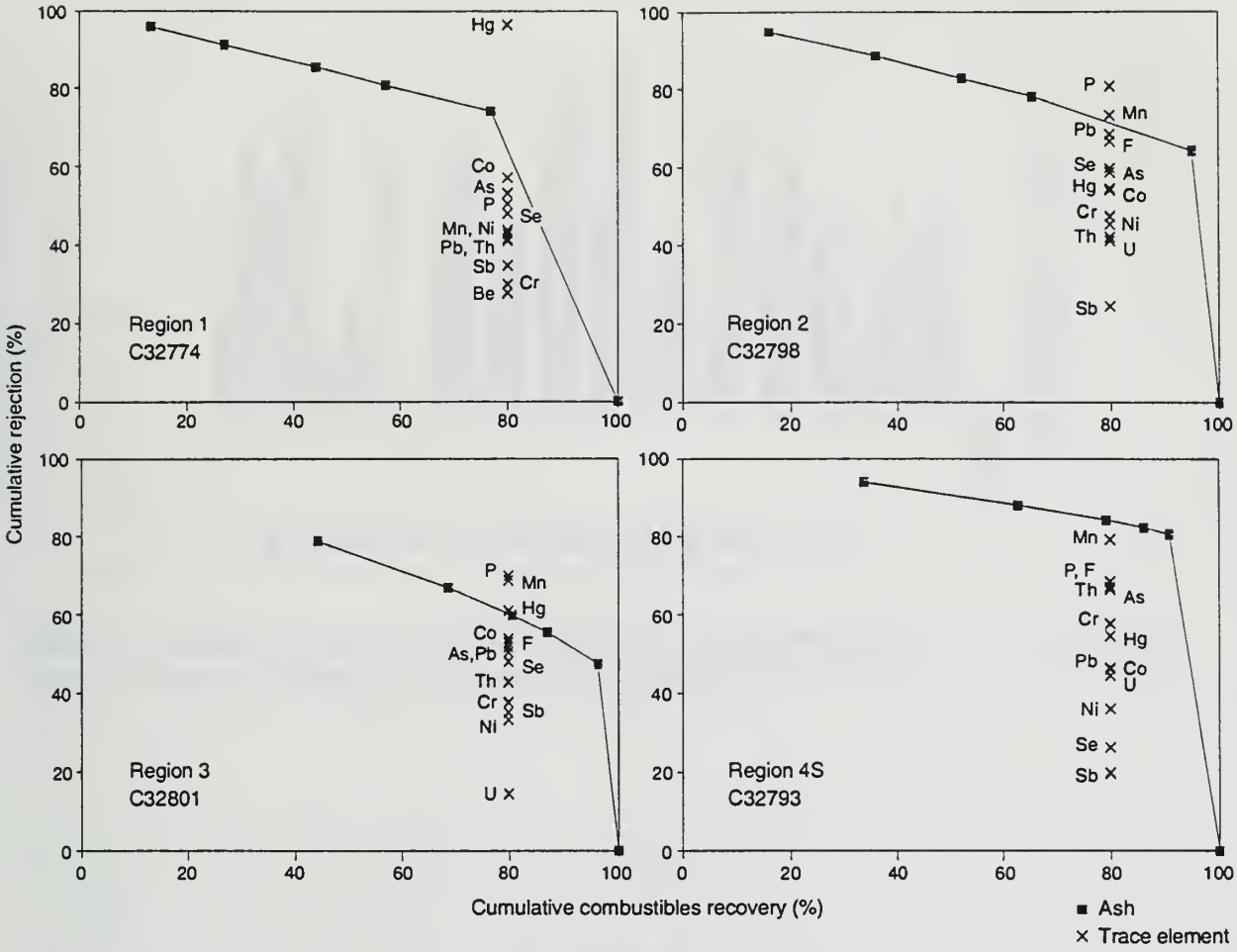

Figure 6 Rejections of ash and HAP elements versus combustibles recovery for four coals ground to -200 mesh and cleaned using the FF/RA process.

Mass Balance Study

Results from FF/RA of one of the as-shipped samples (sample C32796) at -100 and -400 mesh sizes were used to determine mass balances for the test procedures used. This sample was selected because of its high ash yield, high Cl content, and favorable distribution of weights in the FF/RA fractions. All of the various solid concentrate and tailing fractions, representative samples of the water used for grinding and FF/RA tests, and representative sample of the feed coal were analyzed for moisture, ash, total sulfur, forms of sulfur, chlorine, and trace and minor elements. Mass balances achieved (table 5) are generally within analytical and experimental errors, except for sulfatic S.

Excess sulfatic S was generated during grinding and FF/RA. More sulfatic S was generated during the latter than during the former, apparently due to accelerated oxidation of pyrite caused by the introduction of the air bubbles. Most of the sulfatic S was, however, washed away by the process water. The total amount of sulfatic S recovered from the concentrates and tailings was 20% of the original sulfatic S concentration in the feed coal. A considerable portion of Cl was also washed away by the process water because Cl in Illinois coals occurs as dissolved salt and exchangeable anion (Demir et al. 1990, Chou 1991). The total amount of Cl recovered from the concentrates and tailings was 66% and 42% of the original amount for the -100 mesh and -400 mesh FF/RA tests, respectively. Mercury, Mn, and Pb have somewhat higher percent mass

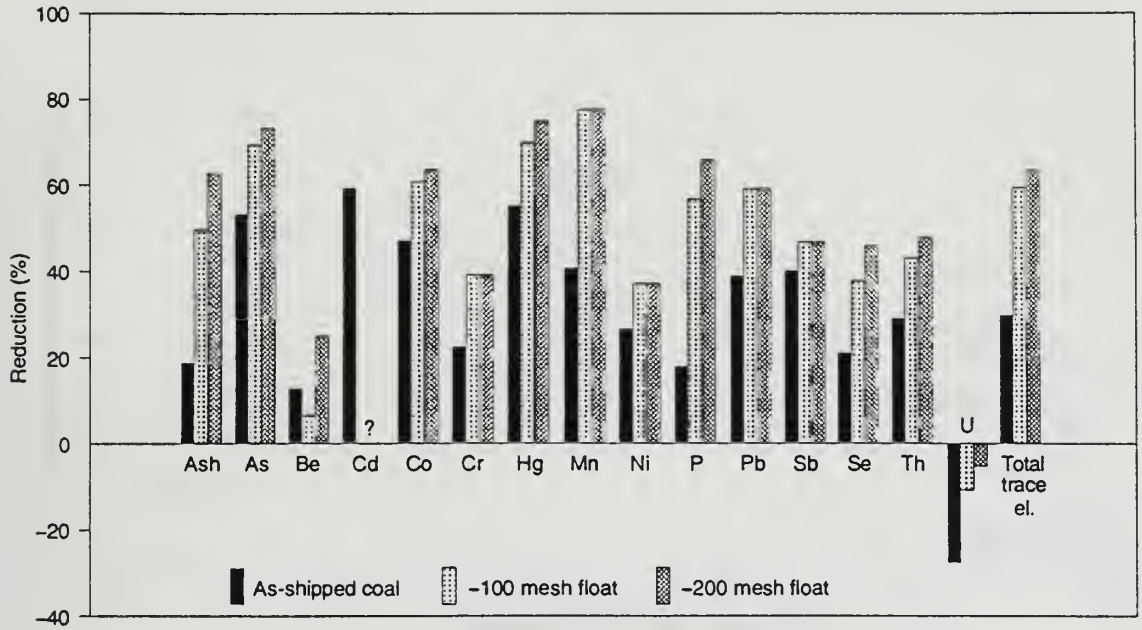

Figure 7 Reductions in average concentrations relative to those in channel samples. -100 mesh and -200 mesh floats represent composites of 80%-combustibles recovery from the FF/RA tests.

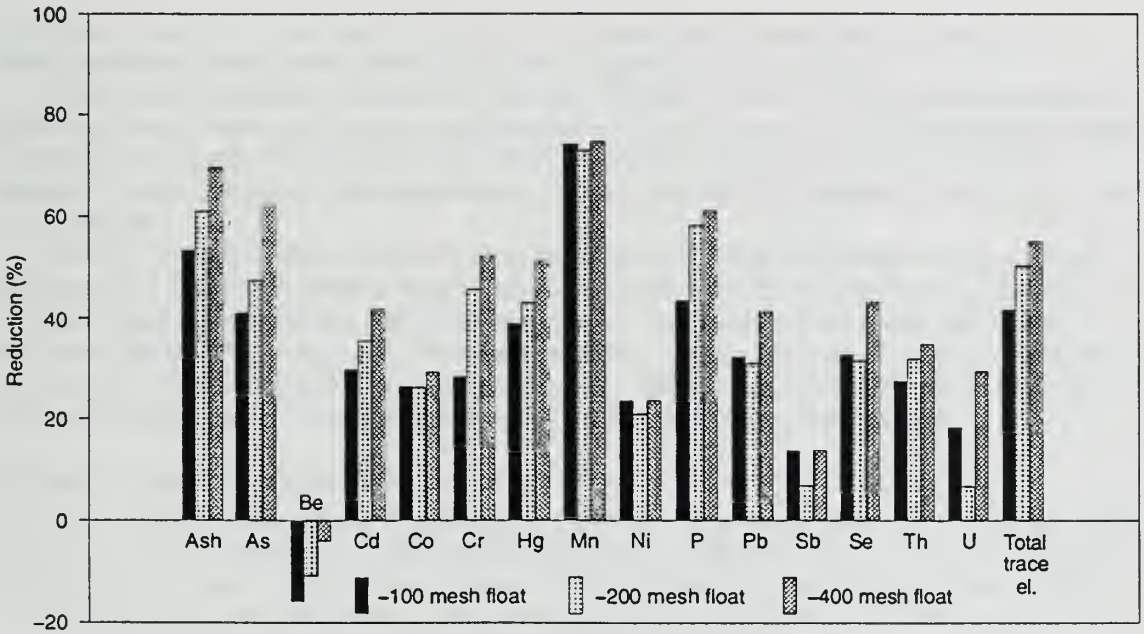

Figure 8 Reductions of average concentrations of ash and HAP elements in FF/RA products relative to those in washed (feed) coals for samples C32774, C32777, C32798, C32801, and C32793. The data for Be and U are averages of four and three samples, respectively.

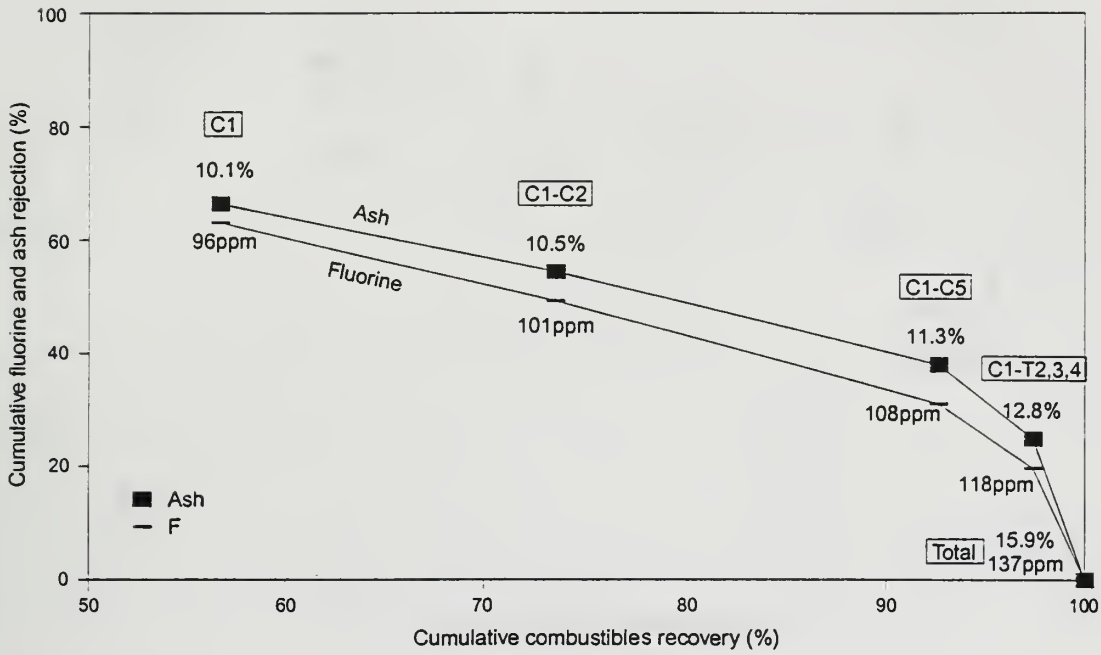

Figure 9 Release analysis curves indicating ash and F rejections versus combustibles recovery for the as-shipped sample C32796 ground to -100 mesh and cleaned through FF/RA. Numbers on the plot are actual ash (in %) and F (in ppm) values of the indicated cumulative concentrate (C1, C2, etc.) and tailing (T1, T2, etc.) fractions.

balances for the -400 mesh test than for the -100 mesh test. Present data cannot confirm whether this suggests a minor contamination during grinding in the rod mill.

Mass balance data can be plotted to generate release curves that indicate the beneficiation obtained in the progressive clean concentrates (C1-C5) and tailings (T1-T4). Examples of release curves are displayed in figures 9 and 10, which show that F removal follows ash removal. Achieving mass balances within experimental errors indicates a high degree of reliability for the data obtained.

Sample C32796, which was used for the mass balance study, is perhaps the most difficult one of the 34 as-shipped coals to clean. Most of the mineral matter in this coal may be in the form of disseminated clay minerals, a large portion of which could easily have remained in clean fractions during FF/RA separation. There is a possibility that for this type of sample, FF/RA may not be as efficient as a modern static tube column for reducing ash yield. Therefore, running column flotation tests on sample C32796 and similar coals should be considered.

SUMMARY AND CONCLUSIONS

Thirty-four washed (as-shipped) coal products collected from Illinois mines were tested at -100, -200, and -400 mesh sizes for froth flotation cleanability of ash and trace and minor elements; some were also tested for froth flotation cleanability of S and Cl. Composite samples of 80%-combustibles recovery were prepared by combining concentrates from the FF/RA tests in proportion to their ash contents. The composite samples as well as concentrate and tailing fractions from the FF/RA tests were chemically analyzed. Conclusions reached are as follows.

- Significant reduction for ash yield and most of the HAP elements is possible when deep cleaning is applied to the washed coals. At 80%-combustibles recovery, as much as 69%, 76%, and 83% reductions in ash yield were observed for the -100, -200, and -400 mesh FF/RA tests, respectively.

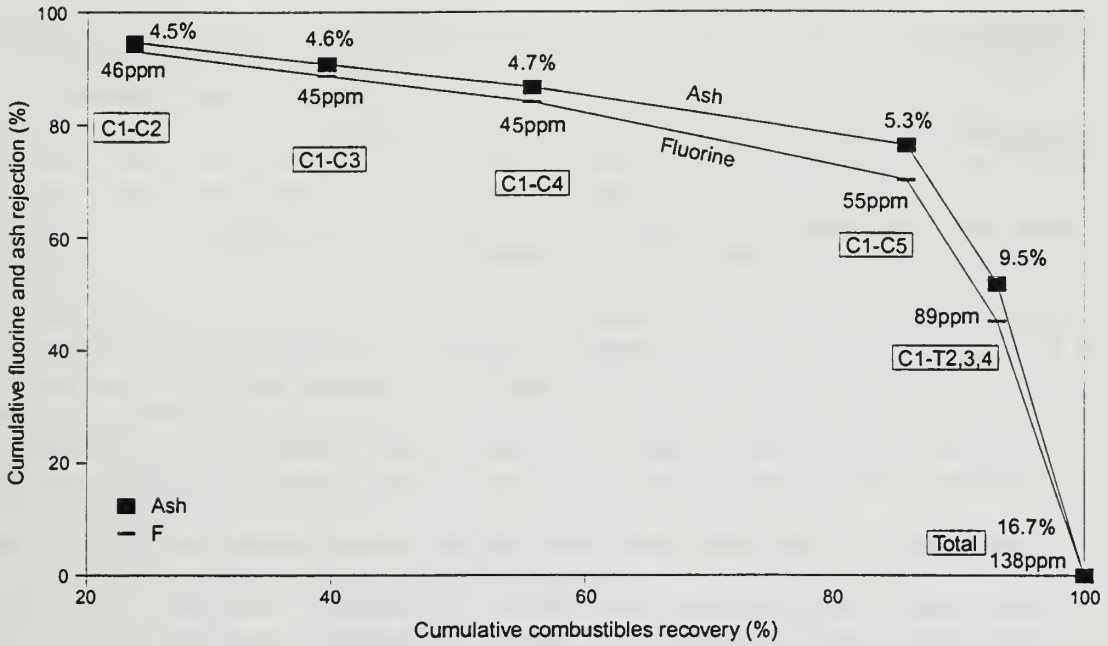

Figure 10 Release curves indicating ash and F rejections versus combustibles recovery for the as-shipped sample C32796 ground to -400 mesh and cleaned through FF/RA. Numbers on the plot are actual ash (in %) and F (in ppm) values of the indicated cumulative concentrate (C1, C2, etc.) and tailing (T1, T2, etc.) fractions.

- The average reductions for most HAP elements were less than those for ash yield. However, reductions for some elements in individual samples approached or exceeded reductions for ash yield. The elements with lower reductions than ash yield apparently are generally concentrated in finely disseminated minerals trapped in the FF/RA concentrates.
- Both the washed coals and their FF/RA products contain significantly less HAP elements than channel samples. In the -200 mesh FF/RA products with 80%-combustibles recovery, for example, average concentrations of As, Hg, and Se were reduced by 73%, 75%, and 46%, respectively, relative to their average concentrations in channel samples.
- Additional FF/RA beneficiation achieved by grinding as-shipped coals finer than -200 mesh is generally small. This is probably a result of trapping of fine ash-forming material in the FF/RA concentrates.
- Mass balances for ash yield, forms of S, Cl, and trace and minor elements were computed for FF/RA tests on one of the coals at -100 and -400 mesh sizes. Mass balances achieved were within analytical and experimental errors, except for sulfatic S; a significant amount of sulfatic S was generated during wet-grinding and FF/RA tests. However, a large portion of sulfatic S, as well as Cl, was washed away by the process water.
- It is possible that for samples with high contents of finely disseminated mineral matter, especially clays, FF/RA may not be as efficient as a modern static tube column in reducing ash yield. Therefore, tests on cleaning such samples with column flotation should be considered in the future.

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Table 1 Relative precision and methods for analyses of coal samples.

Element	Relative precision %	Average detection limit	Method* WDXRF	AAS	INAA	OEP	PyrolC
Major and minor oxides							
Al_2O_3	ash 3	0.1 %	X				
CaO	ash 3	0.02 %	X				
Fe_2O_3	ash 3	0.01 %	X				
MgO	ash 5	0.1 %	X				
MnO	ash 5	0.01 %	X				
P_2O_5	ash 5	0.02 %	X				
K_2O	ash 2	0.01 %	X				
SiO_2	ash 1	0.1 %	X				
Na_2O	ash 5	0.005 %	X				
Na_2O	coal 5	0.003 %			X		
TiO_2	ash 3	0.01 %	X				
Trace elements							
As	coal 7	1.0 ppm			X		
B	coal 15	10.0 ppm				X	
Be	ash 5	0.5 ppm				X	
Cd	ash 10	2.5 ppm		X			
Co	coal 5	0.3 ppm			X		
Cr	ash 2	7.0 ppm			X		
Cu	ash 5	2.5 ppm		X			
F	coal 10	20.0 ppm					X
Hg	coal 15	0.01 ppm		X**			
Li	ash 12	5.0 ppm		X			
Mo	coal 10	10.0 ppm				X	
Ni	ash 10	15.0 ppm		X			
Pb	ash 20	25.0 ppm		X		X	
Sb	coal 10	0.2 ppm			X		
Se	coal 10	2.0 ppm			X		
Th	coal 5	0.4 ppm			X		
U	coal 15	3.0 ppm			X		
V	ash 3	8.0 ppm				X	
Zn	ash 7	1.5 ppm		X			

Constituent	Absolute precision (%)	Accuracy (%)	ASTM (1992) method
Moisture	0.02	0.3	D5142-90
Ash	0.10	0.5	D5142-90
Volatile matter	0.24	1.4	D5142-90
Carbon	0.04	0.40	D3178-89
Hydrogen	0.02	0.10	D3178-89
Nitrogen	0.03	0.05	D3189-89
Total sulfur	0.05	0.20	D5016-89
Sulfatic sulfur	0.04	0.20	D2492-90
Pyritic sulfur	0.1	0.2	D2492-90
Organic sulfur	≤0.19	≤0.6	D2492-90
Total chlorine	0.05	0.20	D4208-88
Calorific value	50 Btu/lb	100 Btu/lb	D2015-91

*WDXRF = wavelength-dispersive x-ray fluorescence spectrometry
AAS = atomic absorption spectrometry
INAA = instrumental neutron activation analysis
OEP = optical emission (photographic) spectrometry
PyrolC = pyrohydrolysis and ion chromatography
**Hg by cold vapor atomic absorption spectrometry

Table 2 Heating value (Btu/lb), ash yield, and concentrations of HAP elements in as-shipped coals and in their clean products from FF/RA tests. The clean products represent 80%-combustibles recovery floats for the indicated particle sizes (-100, -200, -400 mesh).

Parent labno	Region*	Feed or FF/RA product mesh size	Btu/lb dry	Ash yield %, dry	Concentrations of HAP elements (ppm, dry)													
					As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32773	1	feed	12808	8.72	1.3	1.0	<0.3	2.3	12	90	0.13	39	11	44	<6	0.2	1.9	1.2	1.7
		100	13728	6.13	1.0	1.2	<0.2	1.8	10	66	0.04	18	11	22	6	0.2	1.4	1.1	1.3
		200	13944	4.62	0.8	1.1	<0.2	1.7	9.4	47	0.03	20	11	22	<4	0.2	1.2	1.0	0.9
C32774	1	feed	13273	7.07	20	4.0	<0.3	3.1	5.8	68	0.22	18	15	96	102	1.2	1.2	0.8	<0.8
		100	14082	3.70	13	4.2	<0.1	1.8	4.8	59	0.10	11	10	96	59	1.0	1.0	0.6	0.4
		200	14180	3.37	12	3.7	<0.1	1.7	5.2	49	0.10	13	11	61	77	1.0	0.8	0.6	0.6
		400	14305	2.53	9.4	3.1	<0.1	1.6	5.0	44	0.11	12	10	57	60	1.0	0.6	0.6	0.5
C32777	1	feed	12451	14.52	5.1	1.2	5.1	1.5	11	78	0.05	205	7	44	36	1.1	1.6	1.1	1.1
		100	13454	7.58	2.7	1.5	<0.2	1.2	9.8	74	0.05	43	5	13	28	0.9	1.1	1.0	1.1
		200	13666	6.23	2.7	1.5	<0.2	1.2	9.5	55	0.05	40	5	13	30	1.0	1.3	0.9	1.2
		400	13853	5.41	2.2	1.5	<0.2	1.0	10	52	0.04	34	6	17	24	0.8	1.0	0.9	0.9
C32778	1	feed	12709	9.8	10	2.2	0.6	4.6	12	70	0.04	38	31	87	14	2.2	1.5	1.5	0.9
		100	13622	5.63	5.8	2.6	<0.2	4.0	9.7	57	0.05	13	29	39	8	2.2	1.0	1.3	1.1
		200	13703	6.16	6.8	2.5	<0.2	3.5	9.5	45	0.01	29	32	48	12	2.1	0.9	1.2	0.9
C32782	1	feed	12503	11.62	2.4	<1	0.4	1.6	14	78	0.07	55	7	87	<6	0.5	1.9	1.1	1.3
		100	13448	6.97	1.3	1.3	<0.2	1.2	10	68	0.04	18	6	31	4	0.4	1.3	0.9	1.4
		200	13791	5.50	1.3	1.1	<0.2	1.0	9.7	43	0.04	22	7	22	6	0.5	1.2	0.8	1.1
C32783	1	feed	12688	12.86	2.2	1.4	<0.3	2.7	11	81	0.07	37	8	44	<6	0.1	1.3	1.3	1.1
		100	13749	6.01	1.5	1.2	<0.2	1.9	9.8	65	0.08	18	7	22	<4	0.1	1.1	1.1	1.0
		200	13909	4.77	1.4	1.0	<0.2	1.7	9.4	52	0.02	16	8	22	<4	0.1	1.2	1.0	1.2
C32785	1	feed	12741	9.75	2.3	1.5	0.4	2.8	17	115	0.07	39	18	131	<5	0.4	3.9	1.3	1.8
		100	13538	6.54	1.6	2.0	<0.3	2.0	12	69	0.07	17	16	35	7	0.4	2.8	1.1	1.8
		200	13873	4.71	1.6	1.4	<0.2	1.8	11	62	0.03	19	16	31	8	0.3	2.6	1.0	1.5
C32797	1	feed	12728	10.29	4.0	1.2	1.3	3.0	13	116	0.04	32	16	87	9	0.6	1.4	1.5	1.9
		100	13739	5.94	2.2	1.8	<0.2	2.2	11	74	0.04	14	14	22	7	0.5	1.2	1.2	1.8
		200	13949	4.38	2.0	1.9	<0.2	2.1	10	71	0.04	17	16	22	7	0.6	0.8	1.1	1.4
C32814	1	feed	13841	6	6.4	2.0	1.0	2.5	5.7	63	0.07	30	12	30	23	1.9	1.3	0.6	8.0
		100	13973	4.17	4.0	3.8	<0.1	1.9	6.0	60	0.08	14	10	17	14	1.7	1.1	0.6	6.9
		200	14199	3.21	3.2	2.2	0.6	1.7	5.6	52	0.05	19	9	13	13	1.6	1.0	0.6	6.3
C32779	2	feed	12753	9.63	1.7	<1	0.4	2.0	17	91	0.05	29	11	44	7	0.4	2.3	1.3	3.1
		100	13830	6.06	1.1	<1	<0.3	1.5	14	78	0.03	12	11	26	6	0.3	1.7	1.1	3.1
		200	13982	4.44	1.0	1.1	<0.1	1.3	13	54	0.02	15	11	22	5	0.3	1.2	1.1	2.8
C32794	2	feed	12685	10.52	2.3	1.1	<0.1	2.8	12	95	0.08	40	14	44	15	0.3	1.9	1.4	2.0
		100	13464	7.07	1.9	2.0	<0.3	2.4	12	83	0.05	18	14	35	15	0.2	1.4	1.3	1.9
		200	13803	5.23	1.3	1.2	<0.2	1.9	10	74	0.05	16	11	31	10	0.3	1.2	1.1	1.8
C32798	2	feed	12285	13.16	2.2	<1	0.4	3.3	23	134	0.05	54	18	87	12	0.3	3.2	1.7	2.7
		100	13564	6.37	1.4	1.6	<0.3	2.2	15	80	0.03	18	12	26	10	0.2	1.5	1.3	2.0
		200	13890	5.05	1.2	1.0	<0.2	2.0	16	59	0.03	19	13	22	5	0.3	1.7	1.3	2.1
		400	14029	4.04	0.9	<1	<0.1	1.8	14	53	0.02	17	12	22	5	0.3	1.4	1.3	1.8
C32800	2	feed	12599	11.39	2.0	<1	<0.2	2.8	23	150	0.06	30	16	87	8	0.4	2.8	1.6	2.9
		100	13460	7.03	1.4	1.1	<0.3	2.1	16	96	0.06	15	11	26	8	0.4	1.9	1.4	1.9
		200	13873	5.05	1.2	1.2	<0.2	1.8	15	66	0.03	16	11	26	<4	0.3	1.6	1.2	2.3
C32813	2	feed	12086	14.7	2.4	1.4	1.1	3.5	42	263	0.06	40	24	305	13	0.7	5.4	2.1	3.7
		100	13353	7.83	1.7	1.9	<0.3	2.6	25	118	0.06	17	16	57	14	0.6	3.5	1.5	2.9
		200	13850	5.35	1.3	1.3	<0.2	2.1	18	102	0.06	15	13	39	10	0.6	2.2	1.2	2.3
C32815	2	feed	12422	12.03	3.0	<1	<0.2	2.7	14	88	0.06	61	10	44	12	0.6	2.1	1.7	1.9
		100	13536	6.72	1.8	1.4	<0.3	2.1	13	80	0.05	19	8	17	7	0.5	1.8	1.4	1.9
		200	13992	4.53	1.2	1.2	<0.1	1.6	12	50	0.03	16	8	13	7	0.5	0.9	1.3	1.8
C32784	3	feed	13329	8.13	18	1.8	<0.3	4.2	11	67	0.11	17	15	61	40	1.1	1.4	1.4	1.0
		100	13704	5.44	13	1.2	<0.2	2.8	9.5	53	0.10	8	12	44	30	1.0	1.2	1.1	0.7
		200	14078	3.68	12	1.6	<0.1	3.0	9.6	33	0.08	8	12	35	35	1.0	1.1	0.9	0.7
C32795	3	feed	13799	5.76	3.6	1.0	<0.1	4.8	8.6	53	0.03	11	18	44	16	1.1	1.1	1.2	0.8
		100	13994	4.00	3.2	1.3	<0.2	4.0	7.6	42	0.04	6	17	39	12	1.0	1.0	1.0	1.0
		200	14184	2.96	2.6	<1	<0.1	3.8	7.4	37	0.03	5	17	31	13	0.9	0.9	0.9	0.7

continued on next page

Table 2 Heating value (Btu/lb), ash yield, and concentrations of HAP elements (*continued*)

Parent labno	Region*	Feed or FF/RA product mesh size	Btu/lb dry	Ash yield %, dry	Concentrations of HAP elements (ppm, dry)													
					As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32796	3	feed	12120	16.1	9.8	1.0	0.9	8.5	19	123	0.06	41	24	87	31	1.0	2.0	3.0	1.0
		100	12908	10.59	6.7	1.9	<0.4	6.5	17	95	0.08	17	19	44	27	0.9	1.9	2.4	0.7
		200	13873	5.21	4.9	1.1	<0.2	4.8	14	54	0.04	12	19	31	21	0.9	1.4	1.6	0.8
C32799	3	feed	12728	11.42	17	1.0	<0.2	4.4	12	127	0.02	64	15	438	64	3.6	1.3	1.6	0.7
		100	13588	6.72	9.0	1.6	<0.2	4.2	10	100	0.02	9.1	11	336	39	3.4	1.3	1.3	0.8
		200	14053	4.04	4.1	1.7	<0.2	3.5	8.2	74	0.01	9.1	13	244	27	3.2	0.9	1.0	0.5
C32801	3	feed	13280	8.36	10	1.0	<0.1	4.4	12	76	0.04	23	14	44	22	0.6	1.5	1.5	1.0
		100	13884	4.86	6.5	1.8	<0.2	2.9	10	60	0.03	8.3	13	22	18	0.5	1.2	1.1	0.9
		200	14003	4.31	6.2	1.1	<0.1	2.6	9.6	46	0.02	9.2	12	17	14	0.5	1.0	1.1	1.1
		400	14168	3.06	4.6	1.4	<0.1	2.4	9.9	50	0.01	9.8	13	17	12	0.6	1.0	1.0	1.0
C32802	3	feed	13094	9.36	3.1	<1	<0.1	2.5	12	88	0.04	23	7	44	7	0.3	1.5	1.4	1.2
		100	13737	5.67	2.4	1.0	<0.2	1.9	11	71	0.04	11	5	22	7	0.3	1.1	1.1	0.9
		200	14078	3.80	1.7	<1	<0.2	1.8	10	68	0.04	10	6	22	5	0.2	0.9	0.9	0.8
C32803	3	feed	13148	9.19	4.1	1.2	<0.1	2.7	12	94	0.04	28	13	44	13	0.4	1.5	1.6	1.1
		100	13734	5.58	2.7	1.0	<0.2	2.0	11	67	0.06	13	8	22	10	0.3	1.2	1.4	1.1
		200	13988	4.22	2.4	<1	<0.2	1.7	10	62	0.05	11	9	17	8	0.3	1.1	1.2	1.5
C32661	4H	feed	13238	8.17	3.4	1.8	<0.3	3.9	16	81	0.07	20	14	44	19	0.5	2.0	1.5	7.5
		100	13696	5.78	2.8	1.6	<0.2	2.5	15	71	0.06	10	11	22	12	0.4	1.5	1.3	6.3
		200	14098	3.78	1.9	1.4	<0.1	2.1	14	58	0.07	9	11	17	13	0.4	1.2	1.0	6.0
C32664	4H	feed	13148	9.87	5.4	1.4	<0.3	4.4	13	87	0.19	20	11	175	33	0.5	1.6	1.7	2.2
		100	13221	8.32	3.8	1.4	<0.3	2.8	12	92	0.08	10	10	26	31	0.3	1.0	1.5	2.0
		200	13722	6.27	3.7	1.3	<0.3	3.0	12	74	0.08	10	10	22	31	0.4	1.0	1.3	2.2
C32665	4H	feed	13151	9.39	4.4	1.2	<0.3	3.6	13	84	0.17	25	11	44	19	0.4	1.7	1.6	5.7
		100	13561	6.88	3.6	1.1	<0.2	2.8	12	76	0.05	14	9	31	14	0.3	1.5	1.4	6.0
		200	13908	5.00	2.9	<1	<0.2	2.4	11	68	0.04	12	9	22	16	0.4	1.4	1.2	5.4
C32771	4H	feed	12616	12.57	3.7	1.1	<0.5	4.1	14	131	0.14	36	10	44	22	0.3	1.4	1.8	2.2
		100	13494	7.40	2.8	<1	<0.2	2.9	12	96	0.06	14	10	26	21	0.2	1.2	1.4	2.1
		200	13878	5.21	2.1	1.1	<0.2	2.7	12	80	0.05	12	10	17	23	0.1	1.2	1.2	1.9
C32776	4H	feed	13182	9.27	2.7	1.5	<0.3	3.6	15	74	0.07	38	12	44	10	0.6	1.7	1.4	1.8
		100	13806	5.21	1.9	2.0	<0.2	2.7	14	55	0.08	15	10	26	6	0.5	1.4	1.0	1.8
		200	14141	3.53	1.5	1.3	<0.1	2.2	12	38	0.05	11	9	22	5	0.5	1.0	1.0	2.0
C32662	4S	feed	13525	7	14	1.4	<0.3	4.4	10	83	0.08	15	17	175	23	1.0	1.3	1.9	1.9
		100	13892	4.58	9.4	1.9	<0.2	2.8	8.6	65	0.08	6.6	15	100	17	0.9	1.1	1.5	1.6
		200	14118	3.60	8.7	1.4	<0.1	2.8	8.6	62	0.04	6.9	15	83	16	0.9	0.9	1.3	1.4
C32663	4S	feed	13102	8.96	34	1.1	<0.3	4.1	11	78	0.25	17	13	144	70	1.4	1.5	1.4	0.9
		100	13547	6.73	23	1.1	<0.3	2.7	11	68	0.20	9.1	11	100	73	1.2	1.5	1.2	0.6
		200	13855	5.40	23	<1	<0.2	3.3	10	64	0.21	11	13	83	70	1.2	1.3	1.1	<0.5
C32772	4S	feed	13274	9.33	8.0	1.0	<0.2	3.9	9.2	75	0.17	39	13	87	27	0.7	1.3	1.3	<1
		100	13566	6.64	5.9	<1	<0.3	2.7	8.8	66	0.10	15	11	57	26	0.6	1.6	1.1	0.7
		200	13924	4.91	4.5	1.1	<0.2	2.5	8.2	55	0.07	12	11	48	23	0.6	0.9	1.0	0.4
C32775	4S	feed	13779	7.67	4.9	1.8	1.1	4.7	14	97	0.21	16	18	61	45	1.2	3.6	1.3	6.8
		100	13682	6.48	3.8	1.7	0.6	3.5	13	83	0.08	11	15	48	36	1.0	3.1	1.2	6.2
		200	13947	4.89	3.2	1.9	<0.2	3.1	13	74	0.10	9.4	14	17	31	1.0	2.4	1.0	5.8
C32780	4S	feed	13123	9.57	3.1	<1	<0.6	1.9	12	75	0.07	24	8	61	12	1.4	2.3	1.2	2.0
		100	13622	6.57	2.4	<1	<0.2	1.5	10	62	0.05	13	5	44	12	1.2	1.8	1.1	1.7
		200	13963	4.77	2.1	<1	<0.2	1.4	9.2	43	0.06	12	5	22	9	1.1	1.5	1.0	1.6
C32781	4S	feed	13773	9.71	4.3	<1	0.5	2.7	12	104	0.11	37	11	44	46	1.4	2.5	1.2	2.0
		100	13456	7.41	2.6	1.1	<0.3	1.8	11	63	0.10	18	11	26	26	1.0	1.8	1.1	1.6
		200	13669	6.64	3.2	<1	<0.3	2.3	11	61	0.10	15	11	22	39	1.2	2.0	1.1	1.7
C32793	4S	feed	12402	14.14	33	1.2	<0.2	5.5	13	124	0.13	39	22	175	36	1.2	1.1	1.8	0.8
		100	13947	4.35	18	1.2	<0.2	4.4	8.0	71	0.09	7.5	18	96	26	1.2	1.0	1.0	0.5
		200	14106	3.37	15	1.9	<0.1	4.0	7.4	53	0.08	11	19	74	26	1.3	1.1	0.8	0.6
		400	14308	2.46	9.6	1.7	<0.1	3.6	6.9	32	0.06	13	17	61	15	1.1	0.9	0.7	<0.5

*See figure 3 for regional locations.

Table 3 Percent reductions of ash yield and HAP elements in 80%-combustibles recovery concentrates produced by FF/RA of as-shipped coals at -100 mesh particle size.

Parent lab no	Region*	Feed mesh size	Ash yield	As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32773	1	100M	30	26	-20		22	17	27	69	54	0	50		0	26	8	24
C32774	1	100M	48	35	-5		42	17	13	55	39	33	0	42	17	17	25	
C32777	1	100M	48	47	-25		20	11	5	0	79	29	70	22	18	31	9	0
C32778	1	100M	43	42	-18		13	19	19	-25	66	6	55	43	0	33	13	-22
C32782	1	100M	40	46			25	29	15	43	67	14	65		20	32	18	-8
C32783	1	100M	53	32	14		30	11	20	14	51	13	50		0	15	15	9
C32785	1	100M	33	30	-33		23	29	40	0	56	11	73		0	28	15	0
C32797	1	100M	42	45	-50		27	15	36	0	56	13	75	22	17	14	20	5
C32814	1	100M	31	36	-90		24	-5	5	-14	53	17	42	39	11	15	0	14
C32779	2	100M	37	35			25	18	14	40	59	0	40	14	25	26	15	0
C32794	2	100M	33	17	-82		14	0	13	38	55	0	21	0	33	26	7	5
C32798	2	100M	52	36			33	35	40	40	67	33	70	17	33	53	24	28
C32800	2	100M	36	30			25	30	36	0	50	31	70	0	0	32	13	34
C32813	2	100M	47	29	-36		28	40	55	0	58	33	81	-8	14	35	29	22
C32815	2	100M	44	40			22	7	9	17	69	20	60	42	17	14	18	0
C32784	3	100M	33	28	33		33	14	21	9	52	20	28	25	9	14	21	30
C32795	3	100M	31	11	-30		17	12	21	-33	51	8	11	25	9	9	17	-67
C32796	3	100M	34	32	-90		24	11	23	0	59	21	50	13	10	5	20	30
C32799	3	100M	41	47	-60		5	17	21	0	88	27	23	39	8	0	19	-14
C32801	3	100M	42	35	-80		34	17	21	25	64	7	50	18	17	20	27	10
C32802	3	100M	39	23			24	8	19	0	52	29	50	0	0	27	21	25
C32803	3	100M	39	34	17		28	8	29	-50	54	38	50	23	25	20	13	0
C32681	4H	100M	29	18	0		36	6	12	14	52	21	50	37	20	25	13	16
C32664	4H	100M	16	30	0		36	8	-6	58	49	9	85	8	40	38	12	9
C32665	4H	100M	27	18	8		22	8	10	71	44	18	31	26	25	12	13	-5
C32771	4H	100M	41	24			29	14	27	57	61	0	40	5	33	14	22	5
C32776	4H	100M	44	30	-33		25	7	28	14	61	17	40	40	17	18	29	0
C32662	4S	100M	35	33	-36		36	14	22	0	56	12	43	26	10	15	21	16
C32663	4S	100M	25	32	0		34	0	13	20	45	15	30	-4	14	0	14	33
C32772	4S	100M	29	28			31	4	12	41	62	15	35	4	14	-23	15	
C32775	4S	100M	18	22	6	45	28	7	14	62	31	17	21	20	17	14	8	9
C32780	4S	100M	31	23			21	17	17	29	46	38	28	0	14	22	8	15
C32781	4S	100M	24	40			33	8	39	9	51	0	40	43	29	28	8	20
C32793	4S	100M	69	45	0		20	36	43	31	81	18	45	28	0	9	44	38
Maximum			69	47	33	45	42	40	55	71	86	38	85	43	40	53	44	38
Minimum			16	11	-90	45	5	-5	-6	-50	31	0	0	-8	0	-23	0	-67
Average			37	32	-25	45	28	14	21	19	57	17	46	20	15	20	17	9
Standard deviation			11	9	35	0	8	11	12	29	11	11	20	16	11	13	8	20
Cases			34	34	24	1	34	34	34	34	34	34	34	30	34	34	34	32

*See figure 3 for regional locations.

Table 4 Percent reductions of ash yield and HAP elements in 80%-combustibles recovery concentrates produced by FF/RA of as-shipped coals at -200 and -400 mesh particle sizes.

Parent lab no	Region*	Feed mesh size	Ash yield	As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32773	1	200M	47	38			28	22	48	77	49	0	50		0	37	17	47
C32774	1	200M	52	40	8		45	10	28	50	28	27	36	4	17	33	25	
C32777	1	200M	57	47	-25		20	14	29	0	80	29	70	17	9	19	18	-9
C32778	1	200M	37	34	-14		24	21	38	75	24	-3	45	14	5	40	20	0
C32782	1	200M	53	48			36	31	45	43	60	0	75		0	37	27	15
C32783	1	200M	63	38	29		37	15	38	71	57	0	50		0	8	23	-9
C32785	1	200M	52	30	7		31	35	46	57	51	11	77		25	33	23	17
C32797	1	200M	57	50	-58		30	23	39	0	47	0	75	22	0	43	27	26
C32814	1	200M	47	50	-10	40	32	2	17	29	37	25	58	43	18	23	0	21
C32779	2	200M	54	41			35	24	41	60	48	0	50	29	25	48	15	16
C32794	2	200M	50	43	-9		32	17	22	38	60	21	31	33	0	37	21	10
C32798	2	200M	62	45			39	30	58	40	65	28	75	56	0	47	24	22
C32800	2	200M	56	40			36	35	56	50	47	31	70		25	43	25	21
C32813	2	200M	64	48	7		40	57	61	0	63	48	87	23	14	59	43	38
C32815	2	200M	62	60			41	14	43	50	74	20	70	42	17	57	24	5
C32784	3	200M	55	33	11		29	13	51	27	50	20	43	13	9	21	38	30
C32795	3	200M	49	28			21	14	30	0	52	6	31	19	16	18	25	-17
C32796	3	200M	68	50	-10		44	28	58	33	71	21	65	32	10	30	47	20
C32799	3	200M	65	76	-70		20	32	42	50	86	13	44	58	11	31	38	29
C32801	3	200M	48	38	-10		41	20	39	50	60	14	60	38	17	33	27	-10
C32802	3	200M	59	45			36	17	23	0	57	14	50	29	33	40	36	50
C32803	3	200M	54	41			37	17	34	-25	61	31	60	38	25	27	25	-36
C32661	4H	200M	54	44	13		46	13	28	0	53	21	60	32	20	40	33	20
C32664	4H	200M	38	31	7		32	6	15	58	49	9	88	6	20	38	24	0
C32665	4H	200M	47	34			33	15	19	78	52	18	50	18	0	18	25	5
C32771	4H	200M	59	43	0		34	14	39	64	67	0	60	-5	67	14	33	14
C32776	4H	200M	62	44	13		39	20	49	29	71	25	50	50	17	41	29	-11
C32682	4S	200M	49	38	0		38	14	25	50	54	12	53	30	10	31	32	26
C32663	4S	200M	40	32			20	9	18	18	33	0	42	0	14	13	21	
C32772	4S	200M	47	44	-10		38	11	27	59	69	15	45	15	14	31	23	
C32775	4S	200M	38	35	-6		34	7	24	52	41	22	71	31	17	33	23	15
C32780	4S	200M	50	32			28	23	43	14	50	36	64	25	21	35	17	20
C32781	4S	200M	32	26			15	6	41	9	59	0	50	15	14	20	8	15
C32793	4S	200M	76	55	-58		27	43	57	38	72	14	58	26	-6	0	58	25
Maximum			78	78	29	40	46	57	81	77	86	48	88	58	67	59	56	50
Minimum			32	26	-70	40	15	2	15	-25	24	-3	31	-5	-6	0	0	-36
Average			53	42	-9	40	33	20	37	37	58	16	56	26	14	32	28	13
Standard deviation			10	10	25	0	6	11	13	26	14	12	14	15	13	13	10	18
Cases			34	34	21	1	34	34	34	34	34	34	34	29	34	34	34	31
C32774	1	400M	64	53	23		48	14	35	50	33	33	41	41	17	50	25	
C32777	1	400M	63	57	-25		33	9	33	20	83	14	60	33	27	38	18	18
C32798	2	400M	69	59			45	39	60	60	69	33	75	58	0	58	24	33
C32801	3	400M	63	54	-40		45	18	34	75	57	7	60	45	0	33	33	0
C32793	4S	400M	83	71	-42		35	47	74	54	67	23	65	58	8	9	61	
Maximum			83	71	23		48	47	74	75	83	33	75	58	27	58	61	33
Minimum			63	53	-42		33	9	33	20	33	7	41	33	0	9	18	0
Average			68	59	-21		41	25	47	52	62	22	60	47	10	37	32	17
Standard deviation			7	6	28		6	15	17	16	17	10	11	10	10	16	15	14
Cases			5	5	4		5	5	5	5	5	5	5	5	5	5	5	3

*See figure 3 for regional locations.

Table 5 Mass balances achieved for ash yield, sulfur, and HAP elements during FF/RA of region 3 sample C32796 at -100 and -400 mesh particle sizes (all values are on a dry basis).

Mesh Size	Sample Id	Weight gm	Ash yield %	Tot.S %	Org. S %	Pyr. S %	Su. S %	Concentrations of HAP Elements (ppm)															
								As	Be	Cd	Cl	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
-100	Feed	600.00	16.73	1.05	0.53	0.42	0.10	9.4	1.6	<0.6	0.38	8.3	19	142	0.06	42	22	74	31	0.9	2	2.9	0.7
-100	Concentrate 1	310.37	10.07	0.79	0.54	0.23	0.02	6.8	1.7	<0.3	0.28	6.6	16	96	0.03	16	20	44	26	1	1.6	2.1	0.8
-100	Concentrate 2	93.81	11.89	0.77	0.51	0.24	0.02	6.5	1.7	<0.4	0.25	6.5	17	117	0.04	20	22	52	26	0.9	2	2.4	0.9
-100	Concentrates 3,4,5	107.91	14.11	0.80	0.51	0.28	0.02	7.6	1.3	<0.5	0.23	7.2	19	136	0.03	24	21	65	32	0.9	1.9	2.8	1
-100	Tailings 2,3,4	35.64	34.41	1.90	0.53	1.33	0.04	20	1.7	4.7	0.08	14	29	252	0.16	105	25	148	48	1.1	3.2	4.9	1.2
-100	Tailing 1	35.59	64.22	1.79	0.66	1.08	0.04	23	2.0	6.2	0.16	22	48	442	0.22	238	32	275	79	1	3.3	8.5	2.2
cum. recovery from FF/RA products		583.32	15.90	0.92	0.54	0.36	0.02	8.7	1.6	<1.0	0.25	8.1	20	137	0.05	37	22	70	29	1	1.9	2.8	1
recovery from flotation water		nd	nd	nd	nd	nd	0.27	<dl	<dl	<dl	0.21	<dl	<dl	28	nd	2	<dl	nd	1	<dl	<dl	nd	nd
total recovery		583.32	15.90	0.92	0.54	0.36	0.29	8.7	1.6	?	0.46	8.1	20	165	0.05	39	22	70	30	1	1.9	2.8	1
% Mass balance (-100 mesh)*		97	95	88	102	86	290	93	100	?	121	98	105	116	83	93	100	94	97	111	95	97	143
-400	Concentrates 1,2	124.68	4.45	0.65	0.50	0.12	0.03	4.6	1.9	<0.1	0.18	4.7	14	46	0.05	13	19	26	40	1	1.8	1.5	0.6
-400	Concentrate 3	81.91	4.71	0.69	0.53	0.15	0.02	4.9	1.6	<0.2	0.18	4.8	14	44	0.05	13	20	26	41	1	1.7	1.6	0.7
-400	Concentrate 4	84.93	4.92	0.69	0.52	0.15	0.01	5	1.2	<0.2	0.19	4.9	13	46	0.03	14	20	26	32	1	1.7	1.6	0.8
-400	Concentrate 5	159.31	6.39	0.72	0.51	0.19	0.02	6	1.2	<0.2	0.18	5.3	14	72	0.04	16	20	35	35	0.9	1.6	1.8	0.6
-400	Tailings 2,3,4	86.35	40.80	1.59	0.48	1.09	0.03	23	1.8	<1	0.10	16	39	339	0.17	125	30	148	82	1.4	2.9	6.2	1.8
-400	Tailing 1	61.09	59.92	1.96	0.41	1.53	0.03	28	1.1	<2	0.06	21	50	431	0.21	221	32	257	70	1.4	3.1	7.5	1.7
cum. recovery from coal		598.26	16.74	0.96	0.49	0.45	0.02	10	1.5	?	0.16	8.4	22	138	0.08	55	23	74	46	1.1	2	3	0.9
recovery from grinding water		nd	nd	nd	nd	nd	0.06	<dl	<dl	<dl	0.03	<dl	<dl	<1	nd	<1	<dl	nd	<dl	<dl	<dl	nd	nd
recovery from flotation water		nd	nd	nd	nd	nd	0.28	<dl	<dl	<dl	0.11	<dl	<dl	39	nd	1	<dl	nd	<dl	<dl	<dl	nd	nd
total recovery		598.26	16.74	0.96	0.49	0.45	0.36	10	1.5	?	0.30	8.4	22	177	0.08	56	23	74	46	1.1	2	3	0.9
% Mass balance (-400 mesh)*		100	100	91	92	107	360	106	94	?	79	101	116	125	133	133	105	100	148	122	100	103	129

nd: not determined
<dl: concentrations determined in the water were below detection limit and, therefore, recoveries could not be calculated.
*: (total recovery/feed)x100